SUI 64-20

ACILITY FORM 602

N64-30505
(ACCESSION NUMBER)

32
(PAGES)

CR-58882

(THRU)

1
(CODE)

28
GORY)

[redacted]

OTS PRICE

XEROX $ 2.00 ph

MICROFILM $ .50 mf

Department of Physics and Astronomy

STATE UNIVERSITY OF IOWA

Iowa City, Iowa

SUI-64-20

Measurements of Energetic Electrons in the Vicinity of the Sunward Magnetospheric Boundary with Explorer XIV *

by

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August 1964

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*Research supported in part by the National Aeronautics and Space Administration under Grant NsG-233-62 and by the Office of Naval Research under Contract Nonr-1509(06).

ABSTRACT

Observations with the satellite Explorer XIV to radial distances of 16 R_E (earth radii) on the generally sunward side of the earth establish the mean geocentric radial distance of the magnetospheric boundary near the sun-earth line as $\sim 11\ R_E$ during May-August 1963, a period of relatively low geomagnetic activity in the epoch six years after sunspot maximum. Isolated "spikes" of electrons having $40 < E_e < 200$ keV and omnidirectional intensities lying between the detector's threshold of $\sim 5 \times 10^3$ and $\sim 10^5\ (cm^2\ sec)^{-1}$ are often but not always observed in a transition region of radial thickness 2 to 3 R_E beyond the magnetospheric boundary. These electrons are interpreted as being in the high energy tail of the spectrum of the quasi-thermalized plasma $E_e \sim 1$ to 10 keV previously observed in this region by Explorer XII [Freeman, Van Allen, and Cahill, 1963] [Freeman, 1964]. The incidence of the spikes and the complexity and intensity of their radial profile increase with increasing K_p. The geocentric radial distances of both the magnetospheric boundary and the outer boundary of the transition region increase with increasing angle from the sun-earth line toward local evening and the latter boundary apparently lies beyond 16 R_E on the local sunset meridian.

Electrons of energies exceeding 1.6 MeV are observed in localized "hot spots" in the transition region near local morning, implying further heating of electrons in the solar plasma as it flows around the magnetosphere. It is suggested that the temporal variations of intensity of electrons $E_e \sim 1.5$ MeV, for example, in the outer radiation zone can be attributed in large part to inward, radial diffusion of electrons $E_e \sim 300$ keV from the magnetospheric boundary when relatively strong electron heating occurs in the adjacent transition-region plasma during geomagnetically disturbed periods; and that a diffusion mechanism operates continuously within the earth's magnetosphere, thus accounting for the sporadic, large increases of intensity of energetic electrons $E_e \sim 1.5$ MeV in the outer radiation zone following periods of geomagnetic activity as being due to a variable source in the transition region.

I. INTRODUCTION

Phenomena in the vicinity of the magnetospheric boundary are of interest in their own right as providing an example of the interaction of a super-Alfvenic, magnetic plasma with an external magnetic field and as doing so on a physical scale which permits observations of "microscopic" details within the interaction region by practical instruments. Further, it seems quite likely that this interaction, or transition, region between the impinging solar plasma and the ordered geomagnetic field is the source of most of the particle population of the earth's radiation belts [cf. early discussion by Van Allen, McIlwain, and Ludwig, 1959].

Coordinated observations of charged particles and of the magnetic field vector with Explorer XII during late 1961 have established the principal physical characteristics of the magnetospheric boundary and of the transition region on the generally sunward side of the earth [Freeman, Van Allen, and Cahill, 1963] [Rosser et al., 1962] [Cahill and Amazeen, 1963] [Freeman, 1964]. A brief summary of this work is as follows (epoch, about 4 years after sunspot maximum):

(a) Usually, though not always, the ordered geomagnetic field terminates abruptly (often within a radial interval of the order of a few hundred kilometers) at a geocentric radial distance lying between 52,000 and 64,000 km (8.2 to 10 earth radii). Sometimes such a discontinuity is not observed within 83,600 km (apogee of Explorer XII). The magnetic discontinuity defines the magnetospheric boundary (magnetopause) in the observational sense.

(b) The intensity of electrons $40 \leq E_e \leq 100$ keV drops precipitously at the magnetospheric boundary from values of the order of 10^5 to 10^6 inside the boundary to values less than $\sim 3 \times 10^4$ (cm^2 sec sr)$^{-1}$ outside. The latter value corresponds to the approximate limit of sensitivity of the S.U.I. magnetic spectrometer in Explorer XII.

(c) Outside of the boundary and within a region of radial thickness 10,000 to 20,000 km (1.6 to 3.1 earth radii) there is observed often, but not always, a more-or-less isotropic energy flux of particles of the order of tens of ergs (cm^2 sec sr)$^{-1}$. The dominant contribution is by electrons whose particle energies are 1 to 10 keV and whose intensities are of the order of 10^9 to 10^{10} particles (cm^2 sec sr)$^{-1}$. (The threshold sensitivity of the detector is about 1 erg (cm^2 sec sr)$^{-1}$; hence this phenomenon may be much more common than observed with Explorer XII but often of lesser intensity.) The particle population within this transition, or interaction, region is interpreted to be a quasi-thermalized plasma which has resulted from the arrest of the directed flow of the solar wind as it encounters the geomagnetic field. These observations provide an operational definition of the transition region.

(d) The magnetic field within the transition region is quite variable in magnitude and direction with peak magnitudes of the order of 30 gammas.

(e) In view of (a) and (d), it is concluded that the magnetospheric boundary is the outer limit of the region within which durable geomagnetic trapping of charged particles is possible.

(f) The theoretically expected shock front /Axford, 1962/ /Kellogg, 1962/ is not observed directly by Explorer XII but is presumed to lie at the outer surface of the region containing the observed hot plasma and disordered magnetic field.

More sensitive measurements of the intensities of electrons $E_e > 40$ keV with Explorer XIV during 1962-63 /Frank, Van Allen, and Macagno, 1963/ /Frank, 1964/ are more definitive than the corresponding ones with Explorer XII and show that the spatial distribution of such electrons near the equatorial plane is characterized as follows:

(a) The omnidirectional intensity is $\sim 10^7$ to 10^8 $(cm^2 \ sec)^{-1}$ within the magnetosphere in the radial range ~ 2 to $8 \ R_E$ (earth radii).

(b) There is a precipitous drop of intensity within about 1000 km in the radial range ~ 10 to 12 R_E near the earth-sun line (local noon).

(c) Toward local morning and local evening the magnetospheric "boundary" is no longer well defined by a single major discontinuity of particle intensity but becomes diffuse and exhibits multiple peaks which undergo large temporal and spatial variations for distances beyond 8 R_E. Similar particle measurements have been reported in preliminary form by Explorer XVIII (IMP-I) experimenters on the basis of observations during November-December 1963 (epoch about six years after solar maximum). Also the existence of hot, isotropic plasma within the transition region has been confirmed /see International Geophysics Bulletin, No. 84, June 1964/ and extensive magnetic measurements /Ness, Scearce, and Seek, 1964/ have been made throughout the region of interest.

The present paper summarizes observations with Explorer XIV of the intensities of electrons $E_e > 40$ keV near the magnetospheric boundary and within the transition region on the generally sunward side of the earth during the period May-August 1963 and considers the significance of the results.

II. INSTRUMENTATION

Explorer XIV was launched on October 2, 1962, into an orbit with perigee altitude of 281 kilometers, apogee altitude of 98,533 kilometers, orbital inclination of 33°, and period of 36.4 hours. The local time of apogee at launch was 0730; it progressed through local sunrise to local midnight, in late January 1963, and through local sunset to local noon, in July 1963. Transmission of data from the satellite was substantially continuous from launch until August 8, 1963. Detailed descriptions of the S.U.I. complement of Geiger-Mueller tubes on Explorer XIV and the interpretation of their responses have been given previously [Frank, Van Allen, Whelpley, and Craven, 1963] [Frank, Van Allen, and Hills, 1964].

Figure 1 shows a representative set of detector responses as a function of geocentric radial distance. Near the magnetospheric boundary and within the transition region, the response (above galactic cosmic ray background) of G.M. tube 213A is attributed uniquely to electrons having $E_e \lesssim 200$ keV since the companion tube 213C with the same geometric factor and direction of "view" shows no discernible response. The 213C has the same proton threshold (500 keV) as the 213A but is equipped with a magnet in its collimator which excludes electrons $E_e < 200$ keV.

The energy range of the electrons which cause the 213A response can be further limited as follows: The efficiency of 213A for detecting electrons through its 1.2 mg cm^{-2} mica window has been measured with a laboratory electron gun. The data for the energy range 28 to 90 keV have been published previously; the efficiency rises from $\sim 10^{-3}$ count per electron at 30 keV to approximately unity at 50 keV [Figure 1 of Frank and Van Allen, 1963]. In view of the very large intensities ($\sim 10^{10}$ $(cm^2\ sec)^{-1}$) of 1 to 10 keV electrons in the transition region, the laboratory calibration of 213A has been extended down to 5 keV in order to determine its efficiency for non-penetrating electrons via the intermediate bremsstrahlung process. On the basis of the overall laboratory calibrations, Table I summarizes the omnidirectional intensities and energy fluxes of electrons of various energies which are necessary to produce a 213A rate of 10 counts sec^{-1}, a typical response in the transition region. For later reference, the corresponding responses of the 302 Geiger-Mueller tube also via the intermediate bremsstrahlung process [Frank, 1962] are included in Table I; they are seen to be negligible in comparison to the cosmic ray background rate of ~ 2 counts $(sec)^{-1}$ for the electron intensities and energies given there.

Table I

Omnidirectional Intensities of Monoenergetic Electrons Corresponding to a 213A Response of 10 Counts $(sec)^{-1}$

Electron Energy (keV)	J_o $(cm^2\ sec)^{-1}$	F ergs $(cm^2\ sec)^{-1}$	Corresponding 302 G.M. Tube Response counts $(sec)^{-1}$
5	10^{13}	8×10^4	--
10	10^{12}	2×10^4	--
15	10^{11}	3×10^3	2×10^{-1}
20	10^9	3×10^1	2×10^{-2}
30	5×10^7	3	5×10^{-2}
40	5×10^4	3×10^{-3}	5×10^{-4}

Explorer XII low-energy electron flux and magnetic field measurements [Freeman, Van Allen, and Cahill, 1963] [Freeman, 1964] and Explorer XVIII magnetic field measurements in the transition region [Ness, Scearce, and Seek, 1964] provide a basis for obtaining a generous upper limit on the possible energy density of the transition-region plasma, which in terms of energy flux ($\sim$ 1 to 10 keV electrons) is 100 to 500 ergs $(cm^2\ sec)^{-1}$. The directed interplanetary solar-plasma energy flux is $\sim 10^{-2}$ to 1 erg $(cm^2\ sec)^{-1}$. Hence, the energy densities of electrons $E_e <$ 15 keV required in order to attribute the 213A response to their bremsstrahlung (Table I) are seen to be physically unacceptable. In the energy range $E_e >$ 20 keV for which direct electron penetration becomes important, the efficiency of the 213 G.M. tube is a very steep function of incident electron energy, rising from $\sim 10^{-5}$ count per electron at E_e = 20 keV to $\sim$ unity at E_e = 50 keV. If, as an example, equal contributions to the response of the detector are assumed to be due to each component of a two component beam of electrons E_e = 20 keV and of E_e = 40 keV and if the differential energy spectrum is taken to be of the form E^{-n}, then $n \simeq 20$. Such a spectrum is judged to be unreasonably steep and hence an effective threshold of $E_e \sim 40$ keV has been adopted.

On the foregoing grounds, the response of the 213A detector in the magnetospheric transition region is attributed to electrons having $40 \lesssim E_e \lesssim 200$ keV.

III. EXPERIMENTAL RESULTS

A series of papers concerning Explorer XIV measurements of electrons $E_e > 40$ keV beyond 8 R_E have been published [cf. Frank, Van Allen, Whelpley, and Craven, 1963; Frank, Van Allen, and Macagno, 1963; Frank, Freeman, and Van Allen, 1964; Frank and Van Allen, 1963b; Frank, 1964]; a more detailed examination of measurements of electrons $E_e > 40$ keV in the vicinity of the sunward magnetopause in the following discussion allows further conclusions. A previously published example of the responses of the four Geiger-Mueller tubes as a function of geocentric radial distance is shown in Figure 1 [Frank, Van Allen, and Macagno, 1963]. At 80,000 km the sun-earth-probe angle is 65° toward local morning. Of specific interest are the responses of the detectors beyond 60,000 km. In this example, the magnetospheric boundary is delineated by the rapid decrease of the response of 213A ($E_e > 40$ keV) at a geocentric radial distance of 69,000 km. Over the radial distance range 75,000 to 90,000 km all four detectors are counting at galactic cosmic ray rates, but from 90,000 to 95,000 km the 213A response increases above the background cosmic ray rate by a factor of ~ 100 while the other detector responses remain at their background cosmic ray rates. In particular it is noted that there is no corresponding peak in the 213C response. Hence, this major intensity "spike" at 92,000 km (as well as the lesser one at 72,500 km) is conclusively identified as being due to electrons having $40 \lesssim E_e \lesssim 200$ keV (cf. Section II). An auxiliary, though non-essential, element of identification comes from noting that the intensity at the sides of the spike varies by a factor of ten within an apparent distance of 500 km whereas for the extreme case of a threshold energy (500 keV) proton moving at right angles to a magnetic field as great a magnitude as, say, 30 gammas, the radius of curvature of its path is 3400 km.

There remains to be considered the possibility that the apparently isolated spike at 92,000 km is an observational artifact caused by the following hypothetical chain of circumstances: The magnetospheric boundary was at 94,000 km as the satellite slowly passed that point, but then was driven inward past the satellite to 69,000 km by a gust of solar wind. Such a case on October 1, 1961 has been previously reported [Rosser, 1963, Figure 4, and discussion] in the radial distance range 62,000 to 54,000 km. It is noted that the "detached spike" case on October 1, 1961 occurred during a notably disturbed period [Van Allen and Whelpley, 1962], in a radial distance range characteristic of the magnetospheric boundary during late 1961 ($\sim 9\ R_E$) and was characterized by an electron spectrum and an ordered magnetic field similar to those inside the magnetospheric boundary.

The detached spikes reported in the present paper on Explorer XIV observations (such as Figure 1) are of quite different character. The moving boundary hypothesis is rejected as an interpretation of these spikes and it is proposed that they are <u>characteristic of the transition region</u> on the following grounds. There is a tendency for the spikes to occur more prominently during disturbed periods as measured by K_p but even for $K_p \leq 4$ they are observed in about 50% of the Explorer XIV passes (both inbound and outbound). They lie in the radial distance range 10 to 14 R_E. The electron spectrum is much softer than that within the magnetospheric boundary and the intensities of electrons $E_e > 40$ keV are (usually) much less. The spikes lie beyond the termination of measurable intensities of electrons $E_e > 1.6$ MeV, an alternative criterion for the lack of trapping conditions. A detailed study of the corresponding Explorer XIV magnetic data will be made later when such data are available. Meanwhile it is noted that the magnetic field data of both Explorer XII and Explorer XVIII consistently show that the magnetic field is disordered beyond 10 R_E.

Figure 2 displays a family of four typical cases of Explorer XIV observations under various conditions. The large intensities (near the sunrise meridian) of electrons $E_e > 40$ keV shown in Figure 2A on 14 October 1962 extends to at least satellite apogee position although the data are obtained at a similar sun-earth-probe angle to that of the data presented in Figure 1, but approximately a week later, thus demonstrating the strong temporal changes in intensities and in the structure of the intensity profiles of electrons $E_e > 40$ keV. For the profile of 14 October the magnetospheric boundary is not unambiguously defined by a single sharp decrease of electron $E_e > 40$ keV intensities as is the case in Figure 1, but it is of importance to note that the radial termination of measurable intensities of electrons $E_e > 1.6$ MeV (at 72,000 km in Figure 2A) is approximately coincident with the position of a single precipitous decrease in electron $E_e > 40$ keV intensity. All of the examples of Figures 1 and 2 suggest the termination of the $E_e > 1.6$ MeV electron intensity as an alternate method of defining the radial extent of durable trapping of electrons within the earth's magnetosphere and hence the position of the magnetospheric boundary. The (rare) "spike" of 302 G.M. response ($E_e > 1.6$ MeV) at 90,000 km of Figure 2A has been identified as due to penetrating electrons $E_e > 1.6$ MeV rather than due to penetrating protons $E_p > 23$ MeV by noting that the characteristic Larmor radii of protons $E_p > 23$ MeV in these regions greatly exceeds the width of the peak (~ 1000 km). In Figures 2B and 2C are shown the intensity profiles of electrons $E_e > 40$ keV, > 230 keV, and > 1.6 MeV for consecutive inbound and outbound passes on June 11, 12, 1963. For both intensity profiles the intensities of electrons $E_e > 40$ keV vary smoothly and then decrease rapidly at a geocentric radial distance of ~ 70,000 km, nearly coincident with the termination of observable electron $E_e > 1.6$ MeV intensities. (Approximately 24 hours separate the measurements at 70,000 km for these consecutive inbound and outbound passes.) Beyond the sunward magnetospheric boundary multiple peaks of electron $E_e > 40$ keV intensity extend to 92,000 km and 83,000 km for the profiles of Figures 2B and 2C, respectively, within the transition region. This characteristic depth of 2 to 3 R_E is in good agreement with the magnetic field measurements of the dimensions of the transition region near the earth-sun line [Ness, Scearce, and Seek, 1964] and the outer termination of these irregular intensity profiles probably corresponds to the position of the transition-shock front. An example of a pass for which no observable electron $E > 40$ keV intensities are found within the transition region is shown in Figure 2D which displays the omnidirectional intensity profiles of electrons for the inbound pass on July 13, 1963; the magnetospheric boundary is taken from this graph to be at a geocentric radial distance of 70,000 km. The above set of profiles provide an instructive, abridged index to the large body of Explorer XIV measurements of electrons in the vicinity of the sunward magnetospheric boundary.

A summary of Explorer XIV measurements of electrons on the generally sunward side of the earth is given in Figure 3, as a function of local time and geocentric radial distance. The magnetospheric boundary is taken to be the position of the innermost major drop of the intensity of $E_e > 40$ keV electrons. Nearly the same position is obtained by the $E_e > 1.6$ MeV criterion. All relevant Explorer XIV data during May-August 1963 are included except for those near local sunset. In agreement with previous studies /Frank, Van Allen, and Macagno, 1963/ /Frank, 1964/ observable electron intensities are often found out to (and presumably beyond) the apogee position of Explorer XIV ($\sim 16\ R_E$) near the sunrise and sunset meridian. A single representative orbit has been included in

Figure 3 to show the character of the orbit in these coordinates. Of the 63 magnetospheric boundary passages depicted in Figure 3 there are 31 cases of observable electron $E_e > 40$ keV intensities within the transition region. The typical radial separation between the magnetospheric boundary and the termination of transition region electron intensities is 2 to 3 R_E near the earth-sun line in agreement with the dimensions of the transition region observed with the Explorer XVIII magnetometers. The characteristic radial extent of the magnetospheric boundary and of the transition region electron intensities is shown in Figure 3 to increase from ~ 11-12 R_E at local noon to ~ 14 R_E at ~ 1600 and from ~ 14 R_E at local noon to 16 R_E and beyond at ~ 1600, respectively. No large difference occurs between inbound and outbound passes although the average radial position of the magnetospheric boundary is perhaps somewhat smaller (by 1 or 2 R_E) for inbound passes.(Ecliptic latitudes at 12 R_E near the earth-sun line are ~ 0° and ~ -35° for inbound and outbound passes, respectively.)

The value of K_p is never greater than 4 during the period of observations shown in Figure 3. The separate distributions of K_p values for the 31 cases of observed transition zone spikes and for the 32 cases of no observed transition zone spikes overlap, the average K_p of the former being 2.5 and for the latter 1.5. No spikes are observed in several cases when $K_p = 0$. Hence there is a tendency for the occurrence of transition zone spikes to be positively correlated with the velocity of the solar wind [Snyder, Neugebauer, and Rao, 1963].

IV. SUMMARY OF EXPERIMENTAL RESULTS

The principal experimental results of the present investigation of the Explorer XIV measurements of electrons $E_e > 40$ keV in the vicinity of the sunward magnetospheric boundary are:

(1) A well-defined trapping boundary for electrons $E_e > 40$ keV on the sunward side of the magnetosphere is defined by a sharp decrease of intensity with increasing geocentric radial distance at $\sim 11\ R_E$ near the earth-sun line. This trapping boundary has been previously shown to be coincident with the position of the magnetopause with simultaneous electron and magnetic field measurements by Explorer XII [Freeman, Van Allen, and Cahill, 1963].

(2) The trapping boundary for electrons $E_e > 40$ keV of (1) above is also approximately coincident with the termination of observable intensities of electrons $E_e > 1.6$ MeV. The position of termination of electrons $E_e > 1.6$ MeV intensities may be used to extend the observational definition of the radial extent of durable trapping on the evening and morning sides of the magnetosphere where the irregular profiles of electrons $E_e > 40$ keV have a complex structure beyond $\sim 8\ R_E$ (see Figure 2A).

(3) In a region of ~ 2 to $3\ R_E$ in radial thickness adjacent to and outside of the magnetospheric boundary near the earth-sun

line are found intensities of electrons 40 keV $< E_e < 200$ keV from $\sim 5 \times 10^3$ $(cm^2 \ sec)^{-1}$ (threshold intensity of the detector) to $\sim 10^5$ $(cm^2 \ sec)^{-1}$. These intensity profiles are usually characterized by multiple peaks and occur in approximately 50% of the 63 passes of Explorer XIV through the magnetosphere presented here.

(4) The average radial extent of the magnetospheric boundary increases from ~ 11 R_E near the earth-sun line to ~ 14 R_E at a local time of ~ 1600. The radial extent of the termination of observable electron $E_e > 40$ keV intensities in the transition region increases from ~ 14 R_E near the earth-sun line to apogee position of 16 R_E, and presumably beyond, at a local time of ~ 1600 [cf. Frank, Van Allen, and Macagno, 1963; Frank, 1964, for surveys at local morning and evening].

(5) Intensities of electrons $E_e > 1.6$ MeV exceeding the detector intensity threshold of ~ 10 $(cm^2 \ sec)^{-1}$ are not observed near the earth-sun line in the transition region but are found near local sunrise and sunset in these regions during periods of geomagnetic activity (to be reported more thoroughly in a future publication).

(6) A positive correlation of the presence of observable electron $E_e > 40$ keV intensities in the transition region and geomagnetic activity is indicated by an average $K_p = 2.5$ for

the 31 cases of observation of electrons within the transition region and an average $K_p = 1.5$ for the remaining 32 cases for which no observable intensities (i.e., $\gtrsim 5 \times 10^3$ $(cm^2\ sec)^{-1}$) are present.

V. DISCUSSION

Previous measurements of energetic electrons $E_e > 40$ keV within the transition region have been published, although not with the completeness of the present discussion [cf. Frank, Van Allen, and Macagno, 1963] [Frank, 1964]. Further evidence of the presence of such electrons in the transition region has been provided recently by Explorer XVIII measurements with a 213 G.M. tube with a mica window of similar thickness as that used in the present study [Anderson and Harris, 1964] and with a solid-state detector [Fan, Gloeckler, and Simpson, 1964] whose response is attributed to pile-up pulses from electrons $30 \lesssim E_e \lesssim 160$ keV <u>or</u> to singly counted electrons above the detector energy threshold of ~ 160 keV. From the electron calibration data for the solid-state detector of Fan et al. the omnidirectional intensities of electrons necessary to yield 10 counts per second (a typical response of their detector in the transition region) are $\sim 10^8$ $(cm^2\ sec)^{-1}$ at 38 keV or $\sim 10^7$ $(cm^2\ sec)^{-1}$ at 48 keV but only ~ 1 to 10 $(cm^2\ sec)^{-1}$ at $E_e \sim 200$ keV. In view of the facts (1) that the intensities of electrons $E_e > 40$ keV reported here, although obtained over a different time period, are typically two orders of magnitude less than the above requirements in the energy range $40 \lesssim E_e \lesssim 50$ keV, (2) that the efficiency of the solid state detector rises by approximately six orders of magnitude as the electron energy is increased by only a factor of five from 50 keV to 250 keV, and (3) that we are reporting in the present investigation electron $E_e > 1.6$ MeV intensities of approximately $\sim 10\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ for occasional passes of Explorer XIV through the transition region, we suggest that their detector is responding, almost certainly, to electrons $E_e > 160$ keV.

Mechanisms for the production of energetic electrons in the shock-transition region have been suggested by Kellogg [1964], by Bernstein et al. [1964], and by Scarf et al. [1964]. A detailed confirmation of these theories cannot be obtained solely from the observations of electrons $E_e > 40$ keV presented here, but must come from a detailed correlation between these measurements and those of low-energy protons and electrons and of the magnetic fields in these regions. It is already quantitatively reasonable to believe that the high-energy tail of the transition zone distribution of quasi-thermalized electrons in the 1-10 keV energy range [Freeman, Van Allen, and Cahill, 1962] is of adequate intensity to account for the observation of electrons $E_e > 40$ keV reported herein and even of the lower intensities of electrons $E_e > 160$ keV reported by Fan et al. (as supplemented by the discussion above). The primary supply of electrons is thought to be those of energy several hundred electron volts in the solar wind and the energy required is that of the directed motion of the positive ion component of the solar wind as it exists before encounter with the outer fringes of the earth's magnetic field. The appearance of "spikes" of intensity above the 40 keV threshold of our detector presumably indicates localized "hot spots" in the turbulent plasma.

The occasional appearance of electrons $E_e > 1.6$ MeV down-stream in the transition region toward local sunrise (see Figure 2A) and the absence of measurable intensities of electrons of these energies near the sun-earth line provides evidence for continuing acceleration of electrons in the high-energy tail of the spectrum as the transition region plasma moves past the earth's magnetosphere. It is of further interest to note that the appearance of electrons $E_e > 1.6$ MeV in the morning and evening "skirts" of electron $E_e > 40$ keV intensities beyond $\sim 8\ R_E$ is positively correlated with an increase of electron $E_e > 40$ keV intensities in these regions and with geomagnetic disturbance as indicated by the planetary magnetic indices K_p and $\sum K_p$ (cf. Figure 2A, a general survey of electrons $E > 1.6$ MeV is now being completed). Also, it is known that the intensities of electrons $E_e > 1.6$ MeV in the center of the outer radiation zone decrease catastrophically at the onset of severe magnetic disturbance, remain at low values for several days, subsequently increase to a maximum value over a period dependent on the L-shell of interest and then decay relatively slowly over a period of weeks until a new cycle begins [cf. Frank, Van Allen, and Hills, 1964] [Freeman, 1964]. On the basis of the details of the above morphology of energetic electrons in the outer zone and the appearance of energetic electrons $E_e \gtrsim 200$ keV in the transition region during periods of geomagnetic activity, we suggest that the temporal variations of energetic electrons in the outer zone are the result of inward, radial diffusion of energetic electrons from the transition region into the outer radiation zone over a period of a few days or more (L-dependent) and are intimately related to the sporadic production of relatively large numbers of energetic electrons in the transition region during periods of geomagnetic activity. For example, if an electron $E_e \sim 1.5$ MeV is supplied to the $L = 5$ shell (heart of the outer radiation zone) by radial diffusion from the magnetospheric boundary at $\sim 10\ R_E$ and the first adiabatic invariant μ is conserved in the process, then the particle energy required at $\sim 10\ R_E$ ($B \sim 50\ \gamma$) is 300 keV. Hence, if the intensities of electrons $E_e \gtrsim 300$ keV in the transition region are small during magnetically quiescent periods compared to those during relatively disturbed magnetic periods (as appears to be the case), relatively few electrons $E \gtrsim 1.6$ MeV are supplied to the outer radiation zone by diffusion and the outer radiation zone intensities decrease in accordance with quiescent loss mechanisms. The theory of diffusion of charged particles across L-shells has been treated originally by Parker [1960], Herlofson [1960], and Davis and Chang [1962] and recently by Hess et al. [1964], Mead and Nakada [1964], and Nakada et al. [1964]. Such theories should provide a basis for quantitative interpretation of experimental knowledge to yield a more fundamental understanding of observed diffusion rates, energy spectra, and source strengths. Since a diffusion mechanism for outer zone charged particles will also be reflected in the variation of spectra with geocentric radial distance (or L), we note that at 90,000 km of Figure 2A J_o ($E_e > 40$ keV) $\simeq 10^6$ (cm^2 sec)$^{-1}$ and J_o ($E_e > 1.6$ MeV) ~ 5 (cm^2 sec)$^{-1}$; or if the integral spectrum is represented by e^{-E/E_o} over the energy range 40 keV to 1.6 MeV then $E_o \simeq 120$ keV compared with a typical $E_o \simeq 170$ keV at 45,000 km and $E_o \simeq 340$ keV at 25,000 km near the magnetic equatorial plane [Frank, 1964].

A rough estimate of the relative intensities of electrons $1\ \text{keV} < E_e < 10\ \text{keV}$ and $E_e > 40\ \text{keV}$ in the transition region can be obtained with the Explorer XII low-energy electron measurements [Freeman, 1964] and the present results for $E_e \gtrsim 40$ keV, viz.:

$$\frac{J_o\ (E_e > 40\ \text{keV})}{J_o\ (1\ \text{keV} \lesssim E_e \lesssim 10\ \text{keV})} \sim \frac{10^5\ (\text{cm}^2\ \text{sec})^{-1}}{10^{10}\ (\text{cm}^2\ \text{sec})^{-1}} = 10^{-5}\ .$$

Detailed correlations with simultaneous Explorer XIV magnetometer measurements are expected to provide further conclusions concerning the observations of electrons $E_e > 40$ keV in the vicinity of the magnetospheric boundary reported here.

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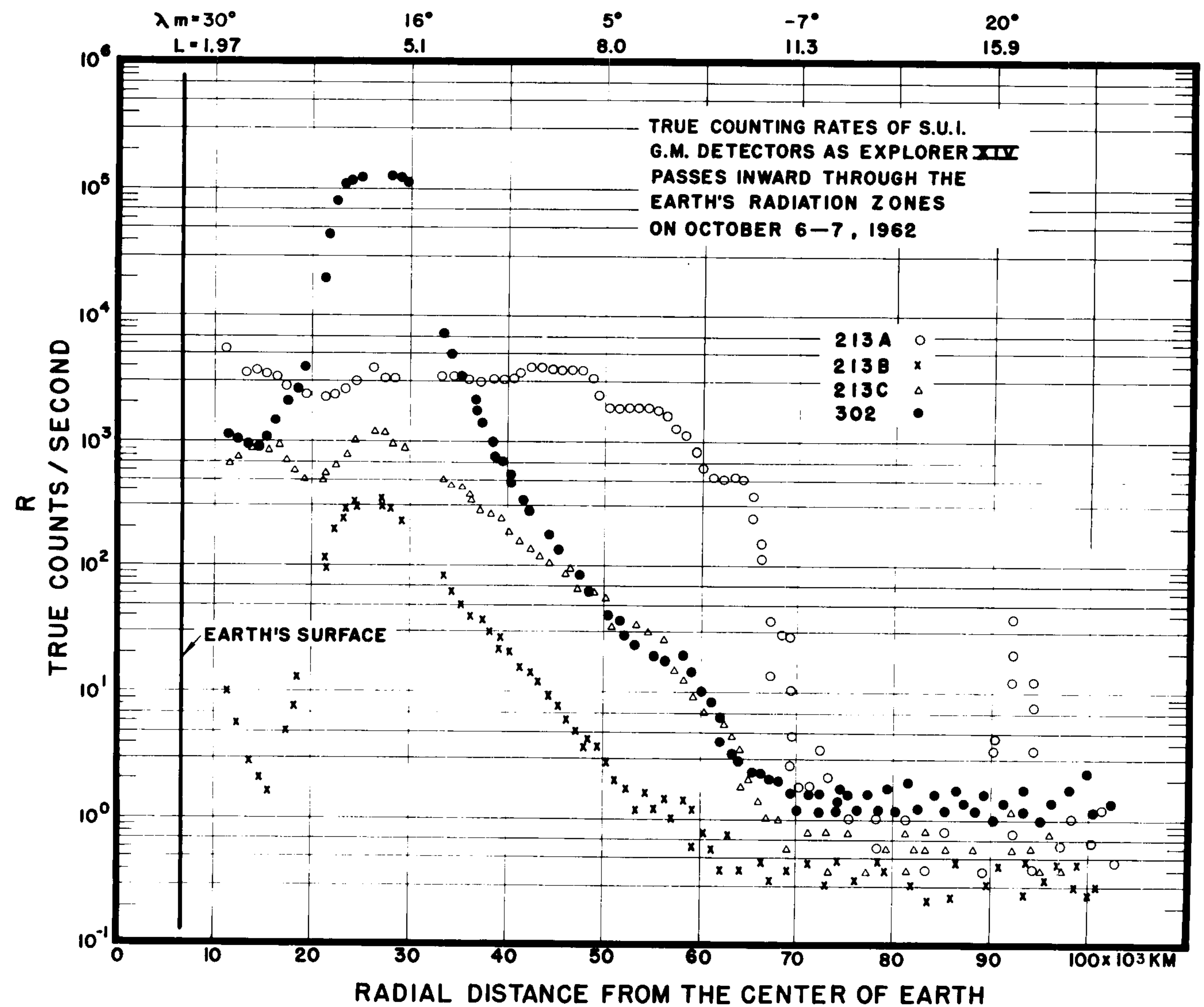
FIGURE CAPTIONS

Figure 1. A previously published profile of the responses of the four S.U.I. Geiger-Mueller tubes on Explorer XIV as a function of geocentric radial distance. The sun-earth-probe angle L_{SEP} at 80,000 km is $\sim 65°$ to the west of the earth-sun line [Frank, Van Allen, and Macagno, 1963].

Figure 2. Several more examples of measurements of electrons in the sunward magnetosphere and beyond. Local time and geomagnetic latitude at 70,000 km are included for intercomparison of the profiles.

Figure 3. A graphical summary of the positions of the geomagnetic trapping boundary and of the termination of observable intensities of electrons $E_e > 40$ keV in the transition region as viewed in a local time-geocentric radial distance coordinate system. The dashed lines connect observations obtained for an individual inbound or outbound pass. Pairs of numbers 1, 2, and 3 in this graph designate measurements for three sets of consecutive inbound and outbound passes. One sample orbital trace is shown.



λm = 30°
L = 1.97
16°
5.1
5°
8.0
-7°
11.3
20°
15.9
TRUE COUNTING RATES OF S.U.I.
G.M. DETECTORS AS EXPLORER XIV
PASSES INWARD THROUGH THE
EARTH'S RADIATION ZONES
ON OCTOBER 6—7, 1962
213A ○
213B ×
213C △
302 ●
EARTH'S SURFACE
R
TRUE COUNTS / SECOND
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
70
80
90
100×10^3 KM
RADIAL DISTANCE FROM THE CENTER OF EARTH

FIGURE 1

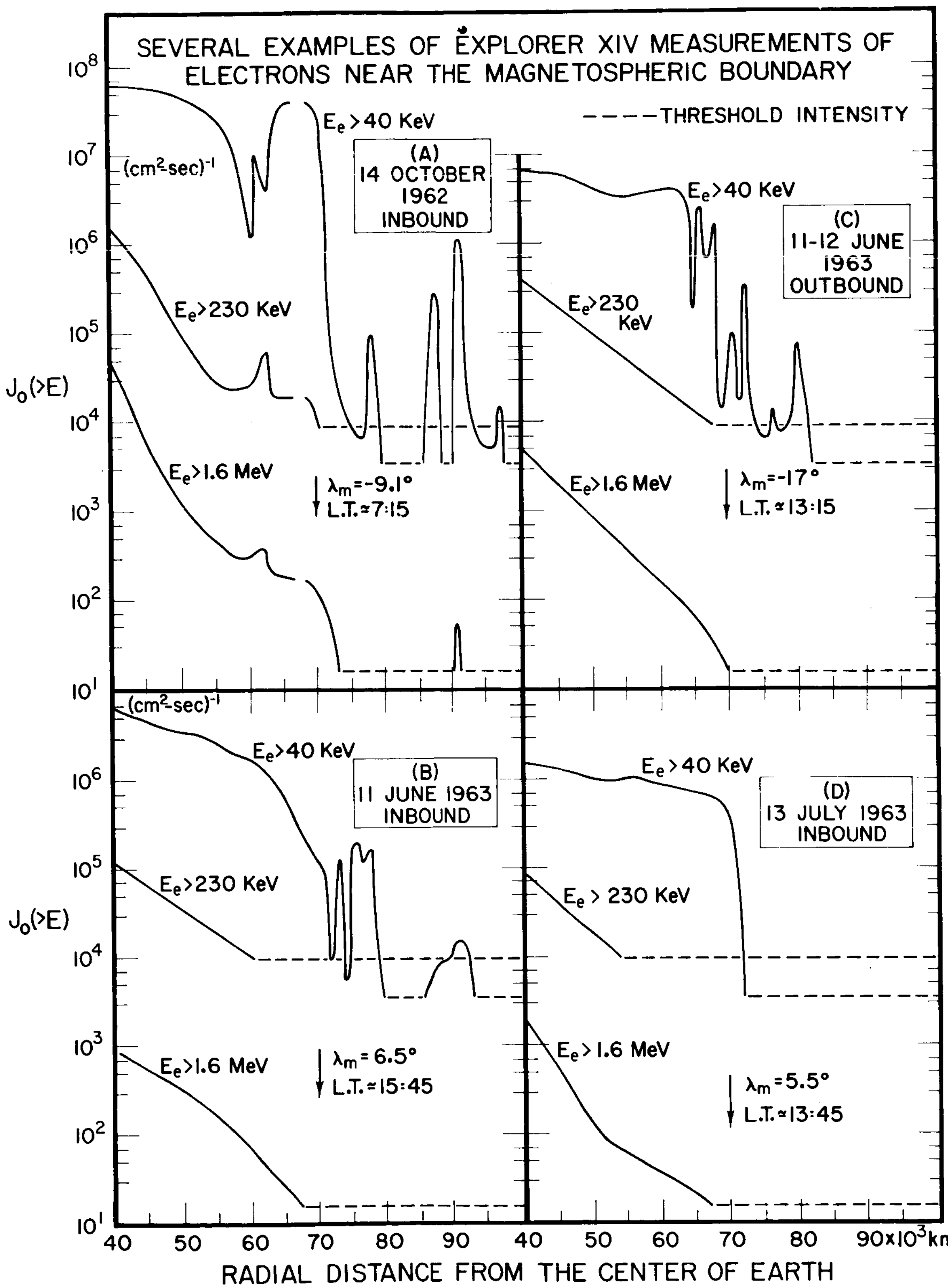

SEVERAL EXAMPLES OF EXPLORER XIV MEASUREMENTS OF ELECTRONS NEAR THE MAGNETOSPHERIC BOUNDARY
----THRESHOLD INTENSITY
(A) 14 OCTOBER 1962 INBOUND
$E_e > 40$ KeV
$E_e > 230$ KeV
$E_e > 1.6$ MeV
$\lambda_m = -9.1°$
L.T. ≈ 7:15
(C) 11-12 JUNE 1963 OUTBOUND
$E_e > 40$ KeV
$E_e > 230$ KeV
$E_e > 1.6$ MeV
$\lambda_m = -17°$
L.T. ≈ 13:15
(B) 11 JUNE 1963 INBOUND
$E_e > 40$ KeV
$E_e > 230$ KeV
$E_e > 1.6$ MeV
$\lambda_m = 6.5°$
L.T. ≈ 15:45
(D) 13 JULY 1963 INBOUND
$E_e > 40$ KeV
$E_e > 230$ KeV
$E_e > 1.6$ MeV
$\lambda_m = 5.5°$
L.T. ≈ 13:45
$J_o(>E)$
$(cm^2\text{-}sec)^{-1}$
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
40 50 60 70 80 90 40 50 60 70 80 90×10^3 km
RADIAL DISTANCE FROM THE CENTER OF EARTH

FIGURE 2

POSITIONS OF THE GEOMAGNETIC TRAPPING BOUNDARY AND OF THE TERMINATION OF ENERGETIC ELECTRONS IN THE TRANSITION REGION AS DETERMINED WITH EXPLORER XIV MEASUREMENTS OF ELECTRONS E>40 KeV

MAY - AUGUST, 1963

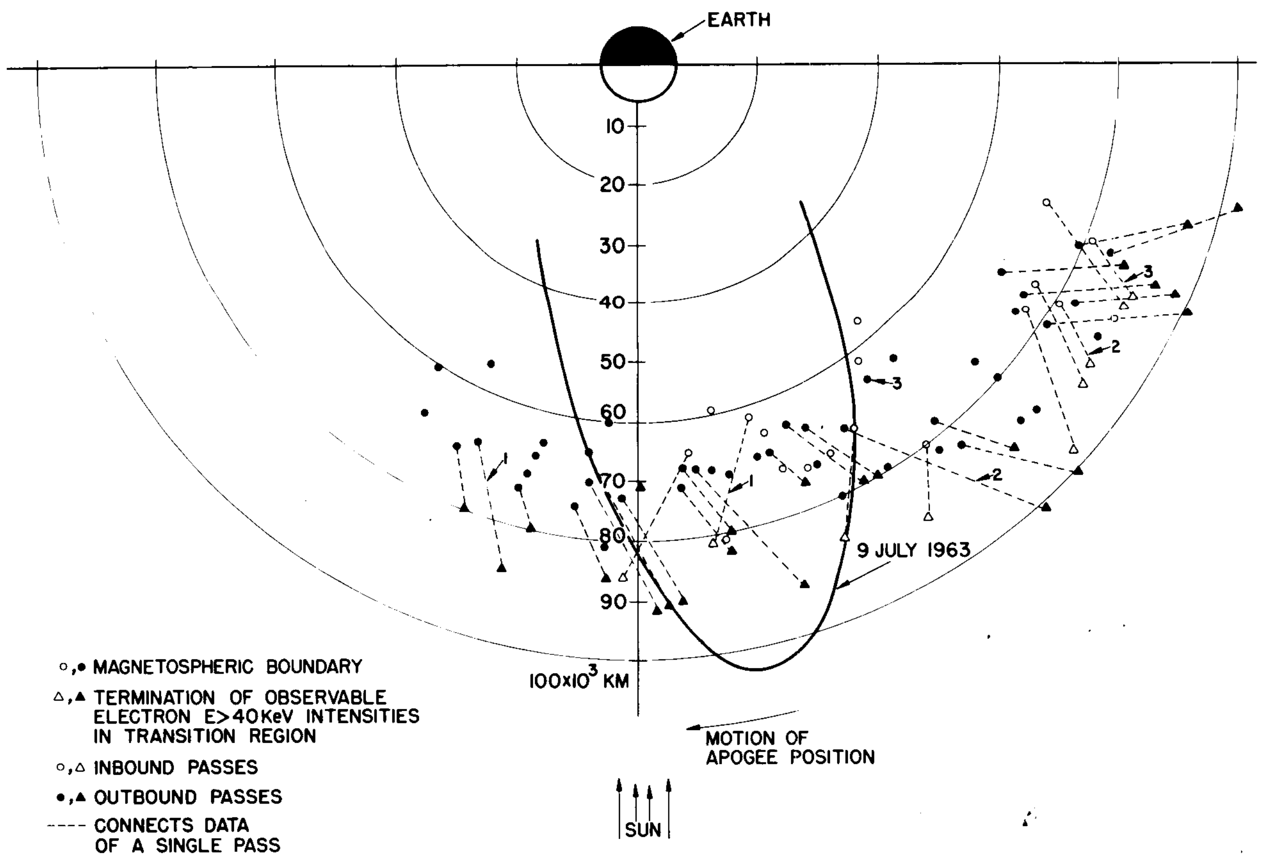


FIGURE 3